Science of the Total Environment 647 (2019) 923–931

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Stormwater volume reduction and water quality improvement by bioretention: Potentials and challenges for water security in a subtropical catchment

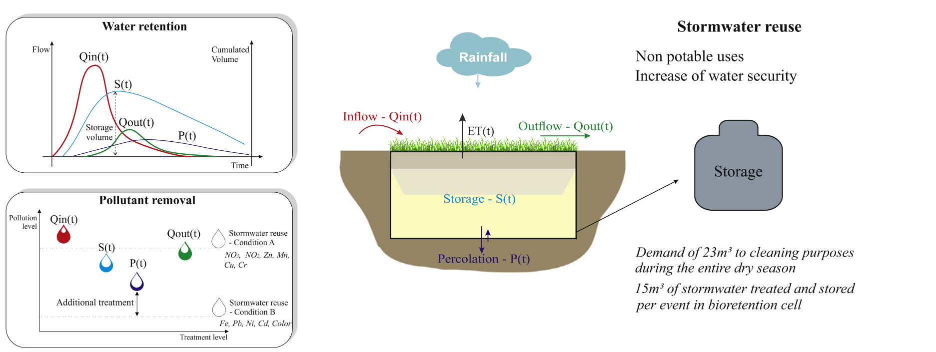
Marina Batalini de Macedo [a],*, César Ambrogi Ferreira do Lago [a], Eduardo Mario Mendiondo [b]

[a] Hydraulic Engineering and Sanitation, University of Sao Paulo, Av. Trabalhador Sãocarlense, 400 CP 359, São Carlos, SP CEP 13566-590, Brazil
[b] University of Sao Paulo, Av. Trabalhador Sãocarlense, 400 CP 359, São Carlos, SP CEP 3566-590, Brazil

HIGHLIGHTS

- Bioretention presents a good runoff reduction capacity (mean efficiency of 70%).
- The results suggest that groundwater replenishment occurs mainly after the event.
- Stormwater reuse directly from the bioretention can be compromised by its quality.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 March 2018
Received in revised form 23 July 2018
Accepted 1 August 2018
Available online 4 August 2018

Editor: G. Ashantha Goonetilleke

Keywords:
Bioretention
Stormwater reuse
Water security
Stormwater harvesting
Pollutant removal

ABSTRACT

Climate change scenarios tend to intensify extreme rainfall events and drought in Brazil threatening urban water security. Low Impact Development (LID) practices are decentralized alternatives for flood mitigation and prevention. Recently, their potential has increasingly been studied in terms of stormwater harvesting. However, there is still a lack of knowledge about their potentialities in subtropical climate regions. Therefore, this study evaluated the behavior of a bioretention cell in a Brazilian city, during the dry period, which is critical in terms of pollutant accumulation and water availability. In addition to the runoff reduction and pollutant removal efficiency, this paper analyzed the potential for water reuse in terms of the stored volume and water quality guidelines. The results obtained show an average runoff retention efficiency of 70%. Considering only the water availability aspects, the potential stored runoff could be reused for non-potable purposes, reducing the water demand in the catchment by at least half during the dry season. On the other hand, the bioretention presented two different conditions for pollutant removal: Condition A – the concentration values are within the recommended limits for water reuse. The parameters found in this condition were NO_3, NO_2, Zn, Mn, Cu, Cr; Condition B – the pollutant concentrations are above the guideline limits for water reuse and cannot be directly used for different purposes. The parameters found in this condition were Fe, Pb, Ni, Cd and color. Considering water reuse, an additional treatment is required for parameters in this second condition. Further studies should evaluate the design aspects that can allow collection of LIDs effluent, additional treatment if necessary, and reuse in the catchment.

* Corresponding author.
E-mail addresses: marinabatalini@usp.br (M.B. de Macedo), cesarlago@usp.br (C.A.F. do Lago), emm@sc.usp.br (E.M. Mendiondo).

https://doi.org/10.1016/j.scitotenv.2018.08.002
0048-9697/

1. Introduction

Rapid urbanization has caused structural and environmental changes in urban basins, increasing paving, reducing soil infiltration and increasing pollutant deposition (Konrad and Booth, 2005; Leopold, 1968; Stovin et al., 2012; Wong and Eadie, 2000). It has also changed social conditions making the population more vulnerable to risks. As a consequence of these changes, there is an important increase in surface runoff, turning natural hydrological cycle risks into urban problems. Extreme rainfall events are precursors of risks to the population (Santos, 2007; Young et al., 2015), who are more vulnerable to floods and landslides. These can be made worse by climate change (Debortoli et al., 2017; Marengo et al., 2010).

Concerning the Brazilian scenario, research carried out by the Brazilian Institute of Geography and Statistics (IBGE) found that more than half of the municipalities in Brazil experienced floods between 2008 and 2012. Among these, the metropolitan region of Sao Paulo was the third city with the highest number of occurrences with a total of 704 floods (IBGE, 2013). During this period, there were deaths in 25% of the flood events in the southeast region. From 2014 to 2016, an extreme drought affected southeast Brazil and the rainfall from January to March was 54% lower than the 1961–1990 reference period (Cemaden, 2015), which caused an unprecedented water crisis in Sao Paulo state. The main supply system in the Sao Paulo metropolitan area, Cantareira, operated at the levels of its dead volume affecting the water security of about 8.8 million people (Escobar, 2015; Tafarello et al., 2016). These extreme droughts also led to other water-related impacts, such as increases in the price of electricity and food (Richards et al., 2015).

Due to the fact that cities are facing these environmental problems and knowing that they tend to become worse with climate change scenarios, the largest cities in the world created the C40 group to discuss and exchange public management actions and policies aimed at reducing the impacts generated and felt by them. In 2014, this group released a diagnostic report and evaluation of its proposed actions. In this report (C40, 2014), 90% of the cities that comprise the group indicated that climate change presents significant risks to their cities; the main ones related to floods and water stress. In addition, they also point to urban drainage as a key to flood risk management, where alternative techniques and systems rank in third place in the group's most accomplished actions. Therefore, the importance of urban drainage can be observed as an adaptation measure to make cities more resilient (Carter et al., 2015). Considering that water stress will become increasingly frequent in these scenarios, alternative drainage techniques that reuse stormwater as a form of urban harvesting (Agudelo et al., 2012) contributes to increasing urban resilience, as well as water, food and energy security.

These alternative techniques have various nomenclatures which are used worldwide, depending on the region and country where they are used. The most used is Low Impact Development (LID) practices, Stormwater Control Measures (SCM) and Best Management Practices (BMP) in the USA, Water Sensitive Urban Design (WSUD) in Australia and Sustainable Urban Drainage Systems (SUDS) in Europe (Eckart et al., 2017; Fletcher et al., 2013). In this study, we will adopt the LID terminology. LID practices aim to reestablish the natural hydrological cycle of pre-urbanization, focusing on water infiltration and integrated efficiency in the runoff amount and pollutant control (Council, 2007; Fletcher et al., 2013; Prince George's County, 2007). Research centers in Melbourne (Australia) and Santa Monica (USA) are pioneers in integrating LID practices in stormwater reuse from stormwater harvesting.

Many studies further evaluate the benefits of separate water retention and flood attenuation (Davis, 2008; Winston et al., 2016) from pollutant treatment and water quality improvement (Bratieres et al., 2008; Davis, 2007), making it difficult to integrate assessments for stormwater harvesting (Lucke and Nichols, 2015; Hatt et al., 2009). This gap is even larger in subtropical regions as most of the studies are conducted in temperate regions, where geoclimatic, sanitary and social conditions are very different from those in subtropical climate areas. Therefore, studying adaptations and monitoring LID practices for tropical and subtropical regions is still a shortcoming, and some questions still remain:

1. Does using stormwater harvesting techniques increase water security in cities?
2. Does only the direct reuse of stored stormwater contribute to the increase in water security?
3. Does the effluent of the LIDs systems have the appropriate quality standard for water reuse?

Aiming to answer these questions, in this study we evaluated the performance of an LID practice of bioretention already installed in an urban subtropical climate basin, designed for flood mitigation purposes. Based on runoff monitoring (volume, flow and pollution), we considered the potential of adapting these techniques to stormwater harvesting, concerning the direct reuse of water and its contribution to increasing water safety.

2. Methodology

2.1. Study site

The bioretention analyzed in this study was created and has been in operation since 2015 at the University of Sao Paulo (USP/SC campus 2) in the city of Sao Carlos. This area is representative of other cities with medium to fast urbanization rates and is classified as Cfa in the Köppen climate classification having a total annual rainfall of 1361.6 mm and an average daily temperature of 21.5 °C. The rainy season occurs from November to April and January has the most rainfall (274.7 mm and average daily temperature of 23.4 °C). The dry season occurs from May to October and July has the least rainfall (28.3 mm and an average daily temperature of 18.5 °C) (EMBRAPA, 2017).

USP/SC Campus 2 is located in the Mineirinho river basin. It was inaugurated in 2005 and is still in an expansion process (in 2015 only 15% of its total area was occupied). Therefore, the influence of land use and occupation changes on the long-term bioretention performance can be evaluated. Moreover, the area is a development axis of Sao Carlos city, mainly with a population of low income and popular housing. The Mineirinho basin presents environmental fragility, with points of irregular sewage deposition (Benini, 2005).

The bioretention catchment has a total area of 2.3 ha representing an urban drainage system on a neighbourhood level scale (terminology from Marsalek and Schreier (2009)) with runoff reaching the Mineirinho river directly. The main contribution to runoff comes from pedestrian paths, roads and classroom buildings (Fig. 1), totalizing 25% of the catchment. The other 75% is mostly grassland.

As for the bioretention device, it has a total surface area of 60.63 m^2 and is 3.2 m deep. Its interior has a filter media composition divided into three layers - soil, gravel and sand - with an average porosity of 35% (Fig. 1). The top layer is composed of natural soil from the region, which is characterized as dark brown with organic matter and a main composition of medium sized sand (40%), 25% fine sand and 16% clay, and it has a hydraulic conductivity of 5.83 $mm \cdot h^{-1}$. This layer has a depth of 50 cm and is covered by four different plant types (*Brachiaria* sp., *Sorghum sudanense*, *Sansevieria trifasciata* and *Cyperus papyrus*) responsible for landscape integration, soil fixation and helps to improve pollutant removal (Hunt et al., 2015).

The intermediate layer is a 70 cm gravel layer, with a diameter of 5 cm and porosity of 40%. The bottom layer is 2 m deep comprising coarse sand, with 1 mm diameter and porosity of 30%. The gravel and sand layers together are responsible for the greater retention of surface runoff volume and qualitative treatment, totaling a volume of approximately 58 m^3. The configuration presented was chosen to achieve the qualitative treatment of sedimentary solids.

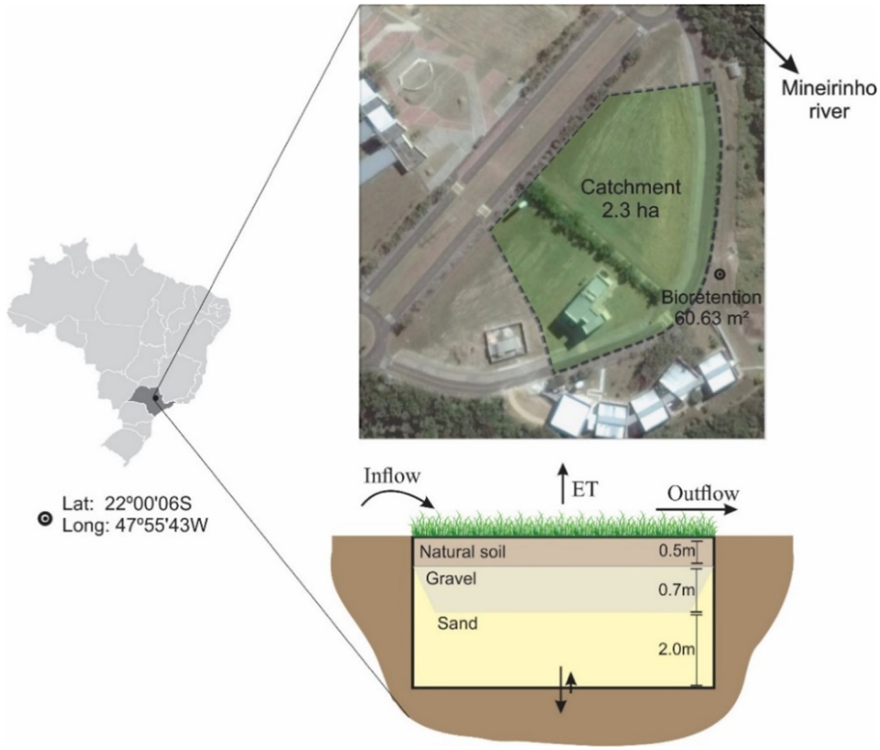


Fig. 1. Study site: Campus 2 USP/SC and bioretention scheme.

The bioretention practice is located at the outlet of the local urban drainage pipe. The water is directed to the device using a rectangular channel, with decanter functions for retaining larger solid particles, equipped with a rectangular-triangular composite section weir, functioning as the inlet structure. Concerning the outlet structure, the system only has a triangular weir for the surface runoff, ensuring a ponding depth of 30 cm. For the subsurface flow, the designed system does not have underdrains for water collection, and therefore all stored water percolates to the ground or is lost by evapotranspiration.

2.2. Analysis of the LID performance in water retention and pollutant control for water security

Data were collected in the bioretention in the field over three years (2015–2017) during rainfall events in the dry season. This period is critical in terms of pollutant accumulation due to the greater deposition of pollutant load in the catchment surface, which is washed-off by the runoff during low intensity rainfall events. This period is also critical in terms of water security because the few rainfall events, which can affect the water supply systems.

The data corresponding to the water balance collected in the field were: inflow, outflow, storage and rainfall. For the inflow and outflow, water level sensors (HOBOU20L-02; Onset; detection limit of 4 mm) were used coupled to the inlet and outlet weir. For the storage, water level sensors were installed in piezometers along the length of the bioretention basin. The precipitated depth was obtained from a rain gauge located at the site. For each of these points and variables, data were collected every minute.

As for the evapotranspiration (ET), three potential or reference ET models (i.e. Hamon, Priestley-Taylor, and FAO Penman-Monteith) were used to obtain daily mean values for each event (Hamon, 1961; Priestley and Taylor, 1972; Allen et al., 1998). The potential ET models of Hamon and Priestley-Taylor indicates the evaporative demand of the environment, considering only meteorological conditions such as daily air temperature for Hamon, and daily air temperature and solar radiation for Priestley-Taylor (Hamon, 1961; Priestley and Taylor, 1972). On the other hand, FAO Penman-Monteith model represents an index of the hypothetical ET for a reference surface without any water deficiency, with 0.12 m of uniform grass covering the entire surface, a constant albedo of 0.23 and surface resistance of 70 s m^{-1}. In this model, the meteorological parameters used are solar radiation, vapor pressure deficit, wind speed, and daily air temperature (Allen et al., 1998). This ET models were also used in other studies evaluating bioretention performance (Nocco et al., 2016). The meteorological data were obtained from the São Carlos weather station of the Brazilian Agricultural Research Corporation - EMBRAPA, which monitors climatic parameters in several Brazilian cities.

Finally, the amount of water percolated to the ground was obtained by water balance (Eq. (1), adapted from Erickson et al., 2013). The total volume obtained for each of the water balance variables were quantified in terms of equivalent depth related to the catchment area.

$$S = (P + V_{in}) - (V_{out} + V_I + V_{ET}) = \left(\frac{Q_{in}(t)\cdot t}{A_w} + P\right) - \left(\frac{Q_{out}(t)\cdot t}{A_w} + V_I + \frac{ET\cdot Ab}{A_w}\right) \quad (1)$$

where: S = storage volume in the bioretention basin [mm]; P = direct precipitation over the bioretention basin [mm]; V_{in} = total inflow volume [mm]; V_{out} = total outflow volume [mm]; V_I = total percolated volume [mm]; V_{ET} = total evapotranspirated volume [mm]; $Q_{in}(t)$ = inflow discharge [m^3/s]; t = analyzed time interval [s]; A_w = catchment surface [1000 m^2]; $Q_{out}(t)$ = outflow discharge [m^3/s]; ET = evapotranspiration over the bioretention surface [mm]; A_b = bioretention surface [1000 m^2].

To complement the analyses, the 30-day Antecedent Precipitation Index (API$_{30}$) was calculated for each event, according to Eq. (2) (Kohler and Linsley, 1951). This index evaluates the previous humidity of the site.

$$API_{30} = \sum_{i=1}^{30}\left[\left(\frac{1}{i}\right)\cdot Pi\right] \quad (2)$$

where: API_{30} = Antecedent Precipitation Index for 30 days [mm]; i = total days of the *i-eth* period before the event in question; Pi = total accumulated precipitation depth corresponding to the *i-eth* period [mm].

Concerning the water quality improvement, the data were collected for the critical period of pollutant accumulation, corresponding to the dry season until the beginning of the rainy season. A total of 12 parameters representing contamination by organic matter, nutrients and metals were analyzed, normally used for rainwater characterization and frequently found in Sao Carlos (Galavoti, 2011). These are: Turbidity, pH, color, Chemical Oxygen Demand (COD), phosphate (PO_4), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), sedimentary solids (SS), Total Organic Carbon (TOC) iron (Fe), zinc (Zn), lead (Pb), nickel (Ni), manganese (Mn), copper (Cu), chromium (Cr), cadmium (Cd). The analysis of these parameters is important to evaluate nutrient cycling, soil and water contamination.

For the quantification of these pollutants in the runoff and the water quality improvement provided by the system, samples were collected for the inlet and outlet structures, and inside the piezometers, corresponding to the inflow, outflow and storage, respectively. The samples were collected every 5 min for the inlet channel and 20 min for the outlet weir and piezometers. The total sampling time was up to 2 h (which represents 6× the time of concentration of the catchment). The laboratory analysis of each parameter was based on the methodology proposed in the Standard Methods for Examination of Water and Wastewater (APHA, 2015). All pollutants were above the detection limit of the methods used.

These pollutants were analyzed in terms of concentration in order to compare them with the water quality standards and guidelines. However, the water quality improvement evaluation from the concentration assessment does not adequately reflect the effect of volume reductions in pollution control. Thus, we also adopted a load approach as a different flow for each time interval influences the total pollutant mass transferred downstream (Lago et al., 2017). The load value was calculated from Eqs. (3) and (4). Finally, the bioretention performance was evaluated according to the indicators presented in Eqs. (5) and (6).

$$EMC = \frac{\int_0^{t_1} C(t)Q(t)\,dt}{\int_0^{t_1} Q(t)\,dt} = \frac{\sum_0^{t_1} C(t)Q(t)\,\Delta t}{\sum_0^{t_1} Q(t)\,\Delta t} \tag{3}$$

$$Load = \int C(t)Q(t)\,dt = EMC \cdot V_{total}/1000 \tag{4}$$

$$PR = P_{percolated}/Pe \tag{5}$$

$$Eff = \pi_{ret}/(Pe + Pi) \tag{6}$$

where: EMC = Event Mean Concentration [mg/L]; $C(t)$ = concentration at time t [mg/L]; $Q(t)$ = water flow at time t [L/min]; t_1 = total event duration [min]; Δt = considered time interval [min]; V_{total} = total volume of input or output [L]; PR = percolation ratio; $P_{percolated}$ = total equivalent depth percolated to the underlying soil [mm]; Eff = water retention efficiency; Pe = total equivalent of runoff arriving at the bioretention input [mm]; Pi = total rainfall depth directly on the bioretention; π_{ret} = total equivalent depth retained by the bioretention [mm].

After collecting the data, the mean value of contamination level in each water balance variable of the bioretention was raised to evaluate the water quality improvement to the runoff. These values were compared with the water quality standards in Brazil. However, a current problem is the lack of specific regulations for water reuse worldwide. The Australian Guidelines for Water Recycling (NRMMC, 2008) were systematized only in 2008, and the Guidelines for Water Reuse produced by EPA (2012) were updated in the USA in 2012. However, in Brazil there is still no specific legislation and the quality standards for rivers and drinking water are used (Resolution CONAMA 357/420, Brazil MMA (2005)).

3. Results and discussion

3.1. Stormwater volume reduction

A total of 14 rainfall events, scattered throughout the dry seasons in Brazil were analyzed for three years. The dry season is critical in terms of pollutant accumulation due to the large antecedent dry period or even due to less rainfall, which is not able to completely wash off the soil. Moreover, this period is also critical in terms of water security due to the small amount of rainfall, which affects the water reservation systems used both for human supply and for energy production (considering that in Brazil most of the electricity comes from hydroelectric power plants) and for food production, which depends on irrigation.

Fig. 2 shows a characterization and water balance of all monitored events. For these events, the total rainfall depth (P_{total}) was low to medium, with Event 3 standing out as the most intense monitored event, with a maximum intensity of 120 mm h^{-1}. Moreover, for Event 3 the percolation ratio was one of the largest, but with a low volume stored inside the bioretention device, with a storage peak reaching 0.41 mm (~10 m^3). This result demonstrates that the bioretention device is working below its total retention capacity. After investigating the causes of this event, we observed soil erosion on the surface of the device and a small amount of established plants (Macedo et al., 2017). Therefore, for the next events, the amount of vegetation was increased. This measure helps increase the water infiltration into the device and the lag time, and also helps to reduce the peak flow as the roots create preferential paths into the soil and the aerial part of the plants increases the resistance to the flow, slowing down the runoff (functioning as an energy disperser).

For the following events, an increase in the storage peak was noted (with the exception of Event 8), varying from 0.55 to 2.17 mm (~13–50 m^3). This result indicates that the vegetation cover has a positive impact because with the increase of the peak storage there was also a rise in the efficiency of water retention.

Regarding the outflow (Fig. 2), the average pattern shows a noticeable runoff reduction transferred downstream. It could also be observed that the output volume has a relation with the storage, but it is not limited by it. Typically, higher storage peak values are associated with higher retained volume and, consequently, lower outflow. However, two points should be raised: (1) outflow is observed even without the stored volume reaching the total bioretention device capacity, concluding that for the monitored events, the infiltration on the vegetated layer was the limiting factor to the outflow; (2) high storage peaks were observed for some events with low water retention efficiency. In these cases, the stored volume is more related with the low percolation into the ground than with the bioretention capacity of runoff volume control.

It is also important to compute the losses by ET over time. The daily ET values were obtained from the average between potential and reference ET models (i.e. Hamon, Priestley-Taylor and FAO Penman-Monteith). The events that resulted in higher ET values were 4, 5 and 6, which correspond to the days with higher solar radiation. Regarding Event 4, the daily ET occurred directly on the bioretention surface reached the highest value (4.6 mm), corresponding to an equivalent depth in the water balance of V_{ET} = 0.012 mm. This amount corresponds to less than 0.2% of the total precipitation, less than 1.5% of the inflow depth and less than 12% of the total percolation estimated for this event. Regarding all the events, the mean values of daily ET corresponded to 0.07 ± 0.05% for the total precipitation depth, 0.41 ± 0.35% for the total inflow depth, and 2.5 ± 3.38% for the total percolated depth. Therefore, during the dry season (corresponding to the austral winter season, with less solar radiation) we noticed that ET was negligible when comparing to the other components of the water balance.

To evaluate the bioretention device performance, we also calculated the water retention efficiency (Eff). The values obtained ranged from

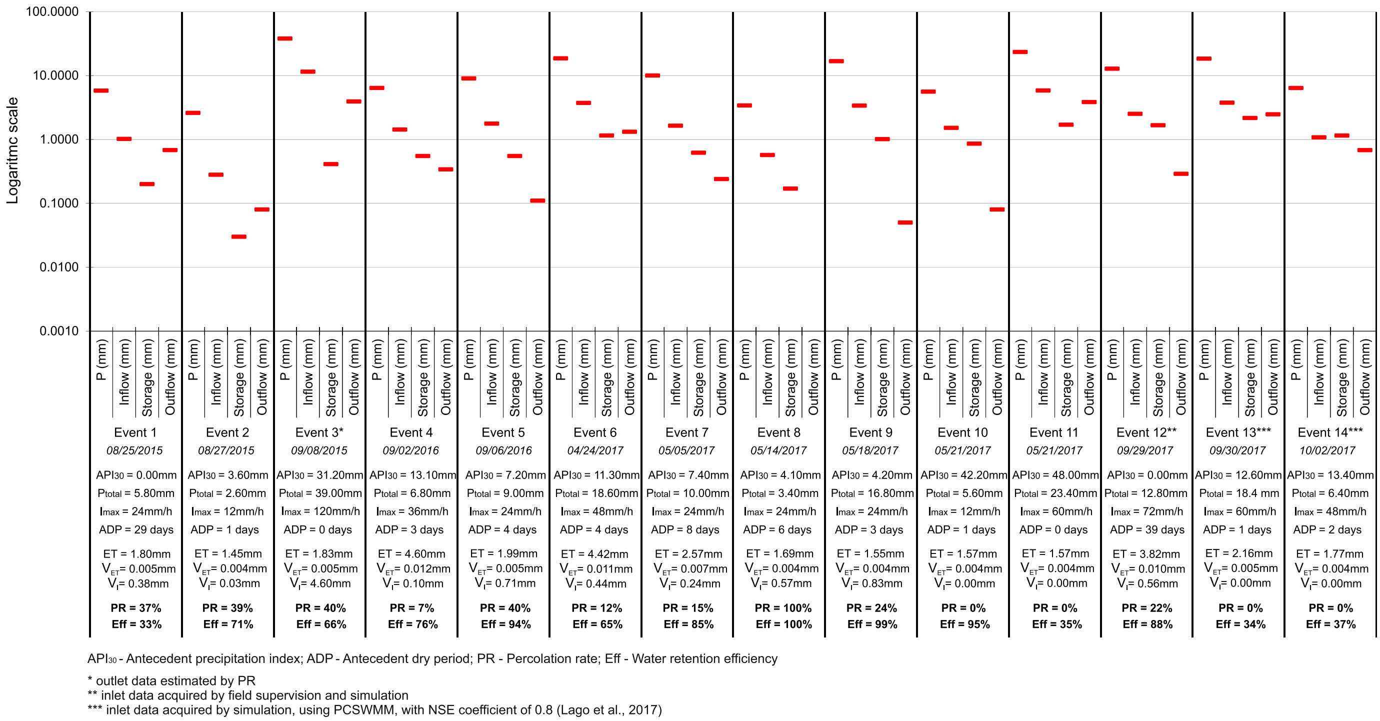


Fig. 2. Water balance per event.

33% to 100%, with an average value of 70 ± 26% (the intervals are presented in terms of standard deviation) (Fig. 2). The volume reduction obtained in this study is higher than that compared with studies developed in other regions (Davis, 2008; Hatt et al., 2009; Lucke and Nichols, 2015; Winston et al., 2016). However, it should be remembered that the monitored events occurred during the dry season, and have a low intensity; therefore, more studies need to be carried out for the rainy season.

An assessment of groundwater replenish was conducted by obtaining the percolation rates in order to evaluate if the bioretention systems also helps to reestablish the water balance prior urbanization, other than just control the runoff peak and volume. The percolation was obtained by the water balance, represented by Eq. (1).

The results obtained show that, generally, the total volume percolated to the ground during the events is even smaller than the outflow volume. This aspect may be associated with ground soil saturation, leading to an increase in the storage, as mentioned previously. The storage will percolate into the ground over time, even after the rainfall has ended, helping to replenish groundwater. The percolation ratio (PR) presented an average value of 24 ± 27%. This variation is related to the soil moisture content and the inflow depth. As for the storage, on the other hand, the values presented a low variation. However, there were extremes of low storage for some events, as Events 1, 2 and 3, when there was still not much vegetation cover.

Fig. 3 shows the hydrographs of events with two different types of behavior. In Fig. 3a, Events 5 and 9 represent the behavior of large peak flow reduction and an increase in lag time, while there is a large reduction in the outflow volume (94% and 99% respectively), called pattern 1. On the other hand, in Fig. 3b the behavior represented by Events 6 and 11 have little or no reduction in the peak flow, and therefore the total runoff retention (65% and 34% respectively) is more important in flood mitigation. This behavior is called pattern 2.

In Fig. 2, these two types of behavior are more explicit: and for the events with pattern 1, the bars between inflow and outflow are more spaced, and usually the outflow is smaller than the storage. Events 4, 5, 7, 8, 9, 10 and 12 correspond to this first behavior. Concerning pattern 2, the inflow and outflow bars are closer together, with a storage value lower than the outflow. Events 1, 2, 3, 6, 11, 13 and 14 correspond to the second behavior. This difference in the patterns seems to be associated with the antecedent dry period, and consequently, the antecedent soil moisture condition. The events of pattern 1 have higher values of antecedent dry periods and lower API_{30}, while those of pattern 2 presented API_{30} values above 11 mm and small antecedent dry periods.

However, some exceptions can be observed. Events 1 and 2 have antecedent dry periods and API_{30} characteristics of pattern 1, but the water balance behavior of pattern 2, which may be associated with a lack of vegetation cover in the soil layer, as previously mentioned. Events 4 and 10, on the other hand, have antecedent dry periods and API_{30} value characteristics of pattern 2, but a water balance behavior relative to pattern 1. This could be explained when analyzing the total rainfall that also influences the water retention efficiency. For these events, besides the higher API_{30} and lower antecedent dry periods, the total rainfall volume was low enough so that the bioretention could retain a greater amount of it.

Therefore, despite the observation of two different behaviors that can be explained by the variables associated with the soil moisture condition, all climatic along with soil characteristics influence the efficiency of the device, and it is not possible to isolate both completely. Therefore, when analyzing only one of the factors it is not possible to regard a clear relation between them and Eff or PR.

3.2. Pollutant removal

In Fig. 2, Events 1 and 12 are the ones with higher antecedent dry periods, leading to high pollutant accumulation in the surface. However, Event 1 has a low total rainfall depth and the pollutant wash off continues to occur in the following events. Therefore, for the pollutant removal analysis, Events 1, 2, 3 and 12 were monitored.

Fig. 4 shows the EMC results obtained for all events at the device inflow, storage and outflow. In terms of concentration, it can be observed that there is no noticeable variation between the three points and the concentration remains practically constant. Only for some pollutants, the outflow value is lower than the inflow, such as COD, TOC, representing organic matter contamination, and metals, Cu and

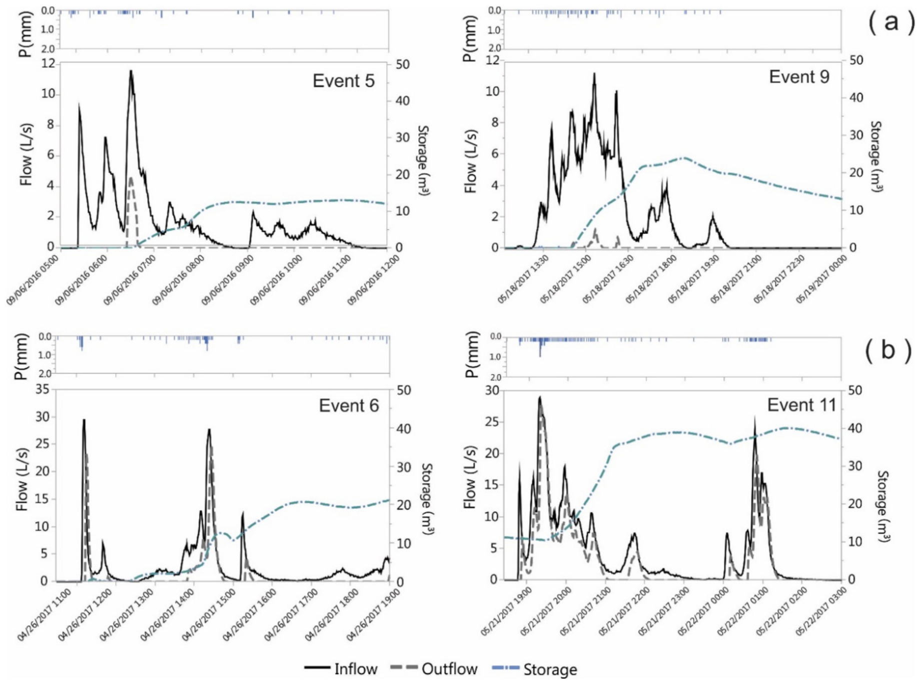


Fig. 3. Hydrographs representing different types of behavior: (a) pattern 1 and (b) pattern 2.

Mn. To better evaluate the pollution level found in the runoff, the concentration values obtained were compared with legislations and guidelines used in Brazil and around the world.

In Brazil, there is still no specific legislation and standards regarding water reuse. The standards and guidelines normally used correspond to specific water uses. For this study, to compare the pollutant level with a standard, the CONAMA resolution 357/420 was used, which presents quality standards for rivers and effluent discharge. The standard values considered were relative to "river class 2", which means rivers that may be for human consumption after conventional treatment, primary contact recreation, irrigation of vegetables and fruit, or any other direct human contact. The standard values for each pollutant are represented by a dotted line in Fig. 4. When there is no dotted line, there is no limit value specified.

In general, for the analyzed catchment, the pollutants representing organic and nutrient contamination in the runoff are within the established standards. Metals, however, are all above the standards, with the exception of Mn and Cr. For Cu, the inflow has a value above the standard, but in outflow and storage the concentration is reduced, complying with the standard. Finally, the color is also above the limit established by the resolution.

To compare with the specific legislations and recommendations for water reuse that are already used worldwide, guidelines from the USA and Australia were also evaluated. Concerning guidelines from the USA, considering unrestricted urban use with the exception of drinking water, for the analyzed parameters only turbidity presents a guideline value, and for this case the runoff is worse than the limit. Regarding Australian guidelines, the standard values for water recycling are the

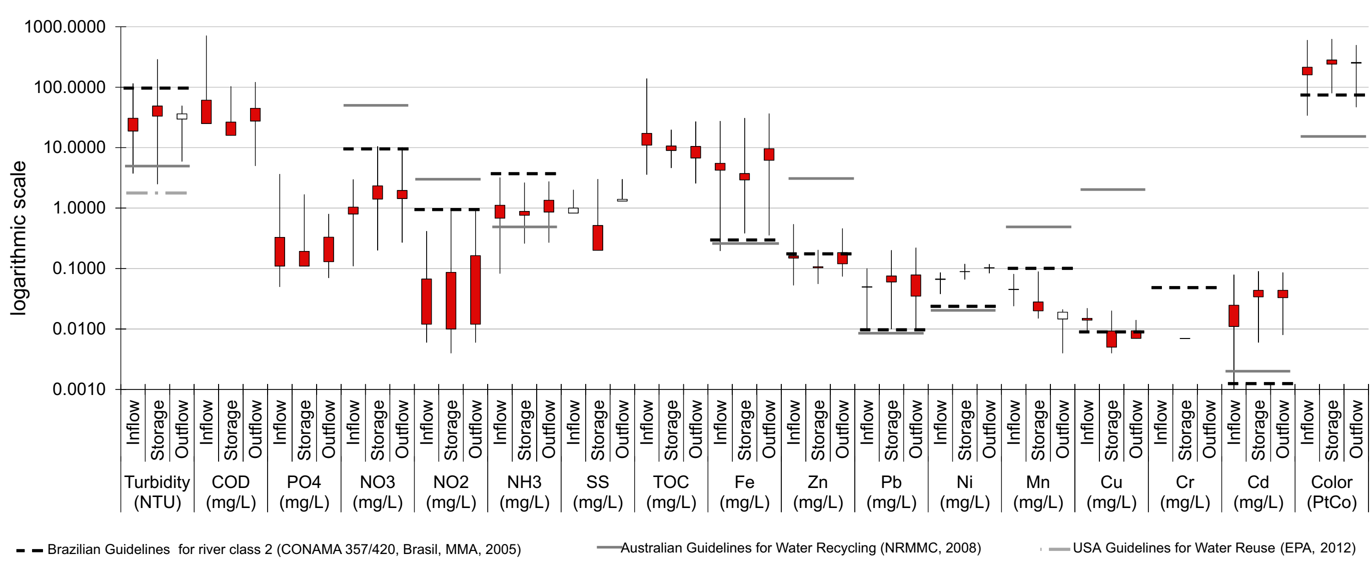


Fig. 4. Event Mean Concentration in each water balance variable of bioretention for n = 100. Dotted lines represent the values of water quality standards and guidelines.

same as those for drinking water. For this case, the turbidity and NH_3 are out of limits, as well as Fe, Pb, Ni, Cd and color. On the other hand, different from Brazilian standards, Zn and Cu comply with the Australian guideline values.

With these results based only on a concentration approach, the bioretention does not appear to be able to treat or assist the pollutant removal. However, it is important to mention the following: (1) despite the fact that the soil layer has a good pollutant removal capacity due to the adsorption process and plant assimilation (Laurenson et al., 2013), the main treatment takes place inside the bioretention device in the sand and gravel layers, where the biofilter and phytoremoval will be established. This happens because inside the bioretention device, the hydraulic retention time is higher than on the surface, favoring non-conservative chemical processes of (bio)degradation, such as denitrification (Erickson et al., 2013; Mangangka et al., 2015). Therefore, the outflow value is expected to remain at the same concentration or slightly lower than the inflow due to a moderate settling (for pollutants bound to particles) and adsorption process in the soil layer. For this configuration, the percolation represents the water actually treated by the bioretention device. (2) Analysis of pollutant removal capacity only by the concentration approach does not take into account the effects of volume attenuation provided by the LID practice, thus presenting an incomplete analysis (Lago et al., 2017).

Therefore, this study also includes the pollutant load approach in order to incorporate the water balance effects to improve the water quality. These results are shown in Fig. 5, in load per square meters. This unit was chosen to present a load unit that could be compared with other bioretentions with different catchment areas.

From the pollutant load approach, almost all the pollutants present an average load reduction, mainly between the inlet and outlet. For storage, this variation is even more noticeable as the infiltrated volume accounts for 12%–40% (with an exception of 100%) of the inflow volume. As an exception, Fe and NO_3 presented no reduction in average loads, rather, an increase in loads was observed. The NO_3 exports are due to the nitrification process that occurs after long drought periods, converting nitrite to nitrate (Bratieres et al., 2008; Davis et al., 2006; Mangangka et al., 2015; Payne et al., 2014). Regarding Fe, this behavior can be explained due to region soil characteristics and a strong erosive process that occurred in Event 3. In the soil layer, natural soil (Red Oxisoil) was used whose main characteristic is the high presence of iron oxide (hematite). In the erosion process in the bioretention, the soil was carried out with the outflow, leading to an export of Fe (Macedo et al., 2017).

3.3. Potential for stormwater harvesting and reuse

Considering the possibility of adapting LID practice to the dual purpose of flood protection and water reuse, through stormwater harvesting, an adaptive design needs to be developed that allows volume storage inside the bioretention device to be collected by lower drains and transferred to individual water reservoirs. In this case, the increasing percolation function provided by the LID practices will be reduced. However, reserving stormwater for multiple uses helps increase water security in the dry season and, consequently, city resilience to climate change. For the bioretention presented in this study, if all stored water were collected by drains, an annual average of 14.8 ± 11 m^3 per stormwater would be reserved during the dry season.

To better assess the contribution of stormwater reuse to increasing water security, the total amount of stored water should be compared to water demands (which need to be quantified). As an example of application, we have assessed the water demands for cleaning purposes close to the catchment area (for the study site, the cleaning is done in the classroom building next to the bioretention). For this purpose, a one-week survey was conducted with the cleaning staff, quantifying all the water expenses required for this type of activity (cleaning bathrooms, and the indoor and outdoor areas). As a result, an average expense was obtained by type of activity. The survey also determined the cleaning routine (what activities are done on which days, how many times a week, and how many times a month). Finally, the calculation of the monthly water demand and during the entire dry season was made by multiplying the expenses by activity per the total amount of activities carried out in the analyzed period.

For this type of water use in the site, there is an average daily demand of 150 L, totaling 27 m^3 in the total dry season. The stormwater volume stored by the bioretention device per event corresponds to half of the cleaning demand, i.e., with two events occurring during this season, the water needs for cleaning purposes can be met. Therefore, the demand for tap and drinking water from public supply systems can be reduced, increasing the local water security during the dry season. However, to meet the demand, stormwater needs to meet water quality standards.

Evaluating the water quality values at the bioretention outflow and storage, the potential water reuse directly from the LID practice can be affected by the pollution level. Two conditions may be found for the water quality improvement through the bioretention for each pollutant parameter: Condition A - the water in the outflow or in the percolated flow reaches the quality standards evaluated, and therefore it can be reused directly after storage; Condition B – the water quality in the outflow and percolated flow is less than the quality standards. Therefore, the guidelines for each type of intended use should be considered in order to choose the reuse that best suits the quality of the water obtained, generating no risks to human health or the environment. One other option is to adapt the system with additional treatment modules to achieve the appropriate quality for the chosen water use.

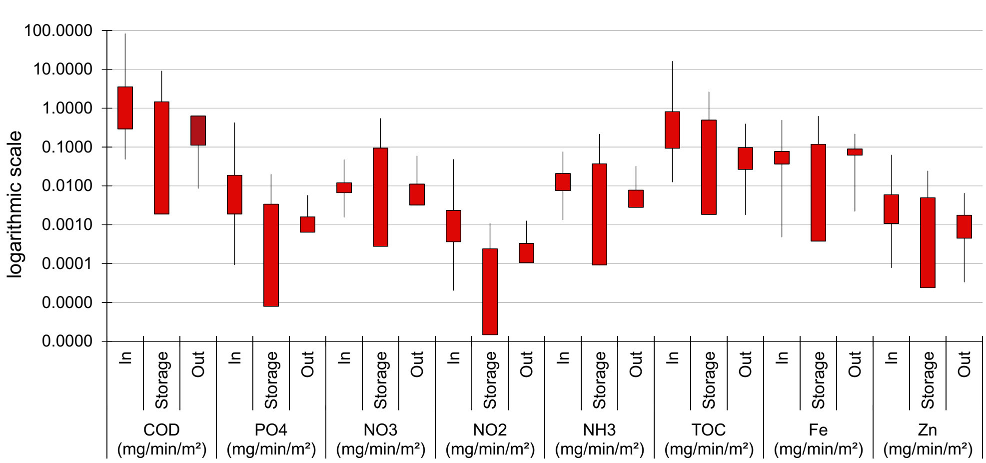


Fig. 5. Pollutant mass balance, for n = 100.

For this study, we observed that the parameters NO_3, NO_2, Zn, Mn, Cu and Cr can be classified in condition A for all the guidelines and standards analyzed, therefore there is no need for further treatment concerning this pollutants. However, for parameters Fe, Pb, Ni, Cd and color, they were above the limits for all the evaluated guidelines, and were suitable for condition B. Concerning turbidity and NH_3, these parameters are within the limits for the Brazilian legislation, but not for the Australian one. Thus, we can conclude that the additional treatment must be done focusing on metal removal as condition B mainly comprises this class of pollutants. It is important to highlight that in this study, we only evaluated the pollution level at the inflow, storage and outflow. However, for the case of stormwater reuse, the water will be collected by underdrain, which should have a better quality.

Additional treatment proposals have already been presented in studies carried out by Mitchell et al. (2007) from other LID types, such as wetlands, conjugated to post disinfection. Moreover, the Santa Monica SMURFF facility uses physio-chemical treatments, more commonly used for water supply and wastewater treatment facilities: coarse and fine screening, dissolved air flotation (DAF), microfiltration and ultraviolet (UV) disinfection (Boyle Engineering Corporation, 1999). For adaptive designs focusing on stormwater reuse, we propose to include studies of effluent treatability during the sizing stage, choosing the best system between biological and physio-chemical treatments. We present the biological treatment with tubular horizontal bed reactors as viable technologies, adapted from Sarti et al. (2006), Zaiat et al. (2000), and Zaiat (2003) and physio-chemical treatments of slow filtration, adapted from Sabogal Paz (2000) and Reali et al. (2013).

Stormwater can be reused and recycled in different ways to increase water security during the dry season: (1) All the stormwater treated by the bioretention cell during the wet season (mainly) can be collected by underdrains and stored in a reservoir, to be directly used in different demands; (2) the overflow of the bioretention cell, which has a better quality then the runoff, will be directed downstream and after going through the process of mixing and dilution in the river, the water can be collected again and used in some of the demands; (3) part of the stormwater treated by the bioretention cell infiltrates to the ground supplying the water sheet. This can increase the river flow during the dry season, amortizing the extreme drought.

4. Conclusion

This study showed that the bioretention device presented a good volume reduction capacity, with average efficiencies of 70%, and the peak flow attenuation for events with a longer antecedent dry period and lower soil moisture was also large (pattern 1). The values of the percolation ratio showed that during rainfall events the percolation was low and the groundwater replenishment occurred mainly after the event, with a transfer of the stored volume to the ground over time. Therefore, the LID practice contributed to reestablishing part of the prior urbanization water balance.

Regarding water quality, the bioretention contribution to the reduction of pollutant concentration in the device outflow and storage was low. For metals, these values were not within the quality standard (CONAMA 357/420, Brazil – MMA, 2005). On the other hand, from the load analysis, which considers the effect of volume reduction, the pollutant removal was more remarkable.

The potential stormwater reuse directly from the LID practice storage can be affected by its quality. It is necessary to choose the reuse that corresponds to the quality value achieved, or adapt the system with additional treatment modules to achieve the standards of the attempted reuse.

Therefore, the LID practices can contribute to increasing the city resilience, both from reducing flood risks and pollutant contamination, as well as increasing water availability and reducing demand for potable uses. However, in order for these systems to achieve this double purpose for these systems, we must ask some key questions during the design phase: how much stormwater can be harvested? How reliable is this supply source? How large a store is required? (Mitchell et al., 2008).

This study addressed a newly established bioretention in an expanding city in a subtropical climate during the dry season (May to October), which is a critical period regarding pollutant accumulation. To better evaluate its performance in flood risk control, further studies need to incorporate the critical period in terms of runoff, which for this subtropical condition is summer (November to April). In addition, adaptations should be made so that it can be used as a stormwater harvesting system, or implement new systems, answering to the key questions previously proposed.

Acknowledgements

CAPES 88887.091743/2014-01 (ProAlertas CEPED/USP), CNPq 465501/2014-1 and FAPESP 2014/50848-9 INCT-II (Climate Change, Water Security), CNPq PQ 312056/2016-8 (EESC-USPCEMADEN/MCTIC) and CAPES PROEX (PPGSHS EESC USP), FAPESP 2015/20979-7 Optimization of operation and maintenance of LID practices in subtropical climate.

References

Agudelo-Vera, C.M., Leduc, W.R., Mels, A.R., Rijnaarts, H.H., 2012. Harvesting urban resources towards more resilient cities. Resour. Conserv. Recycl. 64, 3–12.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper. GAO, Rome.

APHA - American Public Health Association, 2015. Standard Methods for the Examination of Water and Wastewater. American Public Health Association (APHA), Washington, DC, USA.

Benini, R.M., 2005. Cenários de ocupação urbana e seus impactos no ciclo hidrológico na bacia do córrego do Mineirinho. Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos (Dissertation (Master in Hydraulic and Sanitation), in Portuguese).

Boyle Engineering Corporation, 1999. Engineering Report for Dry-weather Runoff, Reclamation, Storage, Pumping, Distribution, and Nonpotable Water Use Area Facilities For City of Santa Monica, Sept 1999, FR-C77-100-02.

Brasil MMA, 2005. Resolução n° 357/420. Ministério do Meio Ambiente, Conselho Nacional do Meio Ambiente, Brasília (in Portuguese).

Bratieres, K., Fletcher, T.D., Deletic, A., Alcazar, L., Coustumer, L., McCarthy, D.T., 2008. Removal of nutrients, heavy metals and pathogens by stormwater biofilters. 11th International Conference on Urban Drainage.

C40, 2014. Climate action in megacities: C40 cities baseline and opportunities. Volume 2.0. Available in: http://issuu.com/c40cities/docs/c40_climate_action_in_megacities/149?e=10643095/6541335, Accessed date: 21 October 2016.

Carter, J.G., Cavan, G., Connelly, A., Guy, S., Handley, J., Kazmierczak, A., 2015. Climate change and the city: building capacity for urban adaptation. Prog. Plan. 95, 1–66.

Centro Nacional de Monitoramento e Alertas de Desastres Naturais [CEMADEN], 2015. Cantareira System: current situation and hydrological prediction. Retrieved February 17, 2015, from. http://www.cemaden.gov.br/cantareira/relatoriosistema-cantareira-10-022015.php (full report updated on 10 Fev 2015, in Portuguese).

Council, Gold Coast City, 2007. Water Sensitive Urban Design Guidelines. Gold Coast City Council, Queensland, p. 2009 (Retrieved October 6).

Davis, A.P., 2007. Field performance of bioretention: water quality. Environ. Eng. Sci. 24 (8), 1048–1064.

Davis, A.P., 2008. Field performance of bioretention: hydrology impacts. J. Hydrol. Eng. 13 (2), 90–95.

Davis, A.P., Shokouhian, M., Sharma, H., Minami, C., 2006. Water quality improvement through bioretention media: nitrogen and phosphorus removal. Water Environ. Res. 78 (3), 284–293.

Debortoli, N.S., Camarinha, P.I.M., Marengo, J.A., Rodrigues, R.R., 2017. An index of Brazil's vulnerability to expected increases in natural flash flooding and landslide disasters in contexto of climate change. Nat. Hazards https://doi.org/10.1007/s11069-016-2705-2.

Eckart, K., Mcphee, Z., Bolisetti, T., 2017. Performance and implementation of low impact development – a review. Sci. Total Environ. 607–608, 413–432.

EMBRAPA, 2017. Condições Meteorológicas Estação da Embrapa Pecuária Sudeste. Available in: http://www.cppse.embrapa.br/meteorologia/index.php?pg=caracterizacao, Accessed date: 1 June 2017 (in Portuguese).

EPA, 2012. 2012 Guidelines for Water Reuse. U.S. Environmental Protection Agency, Office of Wastewater Management, Office of Water, Washington, D.C.

Erickson, A.J., Weiss, P.T., Gulliver, J.S., 2013. Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance. Springer, New York.

Escobar, H., 2015. Drought triggers alarms in Brazil's biggest metropolis. Science 347 (6224), 812.

Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. Adv. Water Resour. 51, 261–279.

Galavoti, R.C., 2011. Proposta de um modelo de gestão integrada de águas urbanas em escala de lote residencial: alcances e limitações. Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos (Thesis (PhD in Hydraulic and Sanitation), in Portuguese).
Hamon, W.R., 1961. Estimating potential evapotranspiration. J. Hydraul. Div. ASCE 87 (HY3), 107–120.
Hatt, B.E., Fletcher, T.D., Deletic, A., 2009. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. J. Hydrol. 365 (3), 310–321.
Hunt, W.F., Lord, B., Loh, B., Sia, A., 2015. Plant Selection for Bioretention Systems and Stormwater Treatment Practices. Springer.
IBGE – Brazilian Institute of Geography and Satistics, 2013. Profile of Brazilian cities. Avaiable in. https://ww2.ibge.gov.br/home/estatistica/economia/perfilmunic/2013/default.shtm, Accessed date: 4 July 2018.
Kohler, M.A., Linsley, R.K., 1951. Predicting the runoff from storm rainfall. US Department of Commerce, Weather Bureau, Washington, DC (Vol. 30).
Konrad, C.P., Booth, D.B., 2005. Hydrologic changes in urban streams and their ecological significance. Am. Fish. Soc. Symp. 47, 157–177.
Lago, C.A.F., Macedo, M.B., Rosa, A., Mendiondo, E.M., 2017. Calibração e validação quali-quantitativa do escoamento superficial - Estudo de caso na USP/São Carlos. XXII Simpósio Brasilieiro de Recursos Hídricos, 2017, Florianópolis (in Portuguese).
Laurenson, G., Laurenson, S., Bolan, N., Beechan, S., Clark, I., 2013. Chapter four – the role of bioretention systems in the treatment of stormwater. Advances in Agrononmy. Elsevier.
Leopold, L.B., 1968. Hydrology for urban land planning: a guidebook on the hydrological effects of urban land use. Circ. No. 554. U.S. Geological Survey, Washington, DC.
Lucke, T., Nichols, P.W.B., 2015. The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. Sci. Total Environ. 536, 784–792.
Macedo, M.B., Rosa, A., do Lago, C.A.F., Mendiondo, E.M., de Souza, V.C. Borges, 2017. Learning from the operation, pathology and maintenance of a bioretention system to optimize urban drainage practices. J. Environ. Manag. 204, 454–466.
Mangangka, I.R., Liu, A., Egodawatta, P., Goonetilleke, A., 2015. Performance characterisation of a stormwater treatment bioretention basin. J. Environ. Manag. 150, 173–178.
Marengo, J.A., Schaeffer, R., Zee, D., Pinto, H.S., 2010. Mudanças climáticas e eventos extremos no Brasil. Available in: http://www.fbds.org.br/cop15/FBDS_MudancasClimaticas.pdf, Accessed date: October 2010.
Marsalek, J., Schreier, H., 2009. Innovation in stormwater management in Canada: the way forward. Water Qual. Resour. 44 (1), v–x.
Mitchell, V., Deletic, A., Fletcher, T.D., Hatt, B.E., McCarthy, D.T., 2007. Achieving multiple benefits from stormwater harvesting. Water Sci. Technol. 55 (4), 135–144.
Mitchell, V.G., McCarthy, D.T., Deletic, A., Fletcher, T.D., 2008. Urban stormwater harvesting–sensitivity of a storage behaviour model. Environ. Model. Softw. 23 (6), 782–793.
Nocco, M.A., Rouse, S.E., Balster, N.J., 2016. Vegetation type alters water and nitrogen budgets in a controlled, replicated experiment on residential-sized rain gardens planted with prairie, shrub, and turfgrass. Urban Ecosystems 19 (4), 1665–1691.
NRMMC, E, 2008. AHMC, Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2): Augmentation of Drinking Water Supplies, Environment Protection and Heritage Council, National Health and Medical Research Council. Natural Resource Management Ministerial Council, Canberra.
Payne, E.G.I., Pham, T., Cook, P.L.M., Fletcher, T.D., Hatt, B.E., Deletic, A., 2014. Biofilter design for effective nitrogen removal from stormwater–influence of plant species, inflow hydrology and use of a saturated zone. Water Sci. Technol. 69 (6), 1312–1319.
Priestley, C., Taylor, R., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100, 81–92.
Prince George's County, 2007. Bioretention Manual. Prince George's County (MD) Government, Department of Environmental Protection, Watershed Protection Branch, Landover, MD.
Reali, M.A.P., Sabogal Paz, L.P., Daniel, L.A., 2013. Tratamento de Água para Consumo Humano. Capítulo 17. Engenharia Ambiental: Conceitos, Tecnologia e Gestão. Elsevier, Rio de Janeiro (in Portuguese).
Richards, R.C., Rerolle, J., Aronson, J., Pereira, P.H., Gonçalves, H., Brancalion, P.H.S., 2015. Governing a pioneer program on payment for watershed services: stakeholder involvement, legal frameworks and early lessons from the Atlantic forest of Brazil. Ecosyst. Serv. Sci. Policy Pract. 16, 23–32.
Sabogal Paz, L.P., 2000. El riesgo sanitário y la eficiência de los sistemas de tratamento en la selección de tecnologías para la potabilizacion del água. Monography. Universidad del Vale, Cali (in Spanish).
Santos, 2007. Vulnerabilidade ambiental: desastres naturais ou fenômenos induzidos? MMA, Brasilia (in Portuguese)
Sarti, A., Sakamoto, I.K., Varesche, M.B.A., Zaiat, M., Foresti, E., 2006. Tratamento de esgoto sanitário utilizando reatores anaeróbios operados em bateladas sequenciais (escala piloto). Engenharia Sanitária e Ambiental 73–82 (in Portuguese).
Stovin, V.R., Moore, S.L., Wall, M., Ashley, R.M., 2012. The potential to retrofit sustainable drainage systems to address combined sewer overflow discharges in the Thames tideway catchment. Water Environ. J. https://doi.org/10.1111/j.1747-6593.2012.00353.x/full.
Tafarello, D., Mohor, G.S., Calijuri, M.C., Mendiondo, E.M., 2016. Field investigations of the 2013–14 drought through quali-quantitative freshwater monitoring at the headwaters of the Cantareira System, Brazil. Water Int. 41 (5), 776–800.
Winston, R.J., Dorsey, J.D., Hunt, W.F., 2016. Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. Sci. Total Environ. 553, 83–95.
Wong, T.H.F., Eadie, M.L., 2000. Water sensitive urban design—a paradigm shift in urban design. Proceedings of the Xth World Water Congress vol. 12 , p. 16. http://gabeira.locaweb.com.br/cidadesustentavel/biblioteca/%7B30788FE6-98A8-44E5-861E-996D286A78B3%7D_Wong1.pdf.
Young, C.E.F., Aguiar, C., Souza, E., 2015. Valorando Tempestades: Custo econômico dos eventos climáticos extremos no Brasil nos anos de 2002–2012. Observatório do clima, São Paulo (in Portuguese).
Zaiat, M., 2003. Desenvolvimento e análise de biorreatores anaeróbios contendo células imobilizadas para tratamento de águas residuárias. Universidade de São Paulo (Tese de Livre Docência, in Portuguese).
Zaiat, M., Passig, F.H., Foresti, E., 2000. Treatment of domestic sewage in horizontal-flow anaerobic immobilized biomass (HAIB) reactor. Environ. Technol. 21 (10), 1139–1145.